Radhard electronics systems of the new CMS Timing Detector at CERN's Large Hadron Collider

J. Varela

PETsys Electronics & LIP/CERN

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Outline

- CERN's Large Hadron Collider & Experiments
- Electronics systems of the CMS Timing Detector
- Performance measurements
- Results on radiation tolerance

See presentation at this workshop:
"Radiation tolerance of the TOFHIR2 chip for the CMS/CERN timing detector"
Edgar Albuquerque, PETsys Electronics SA
Wednesday, June 18, 12:00

The LHC proton collider

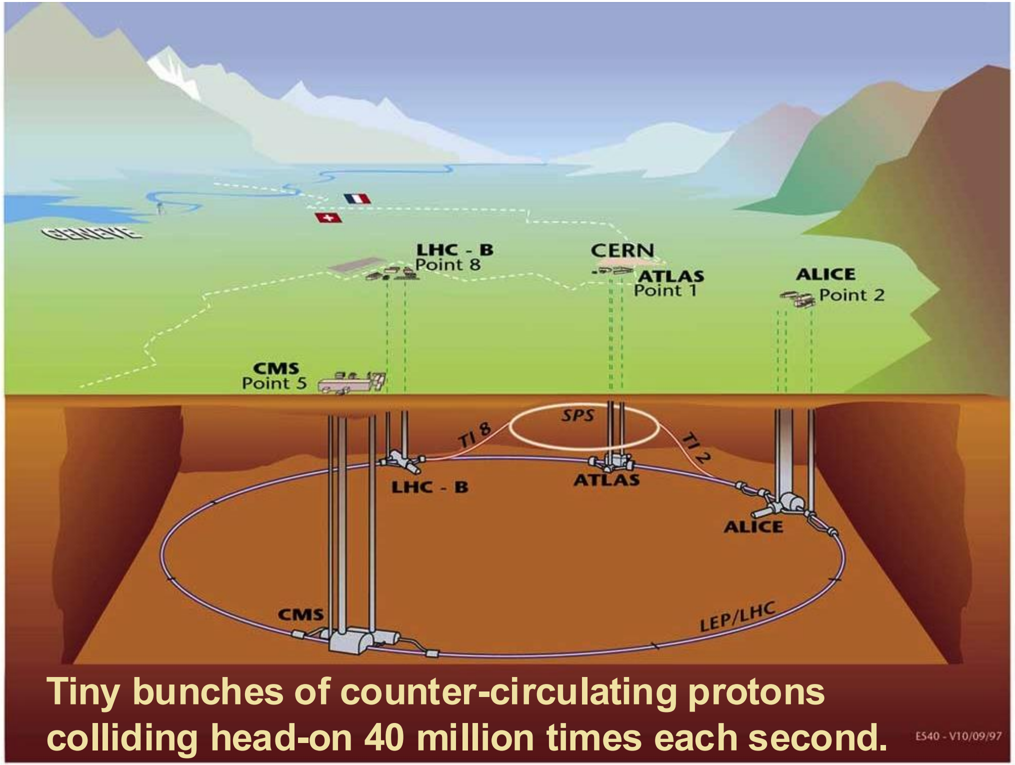
Underground circular tunnel

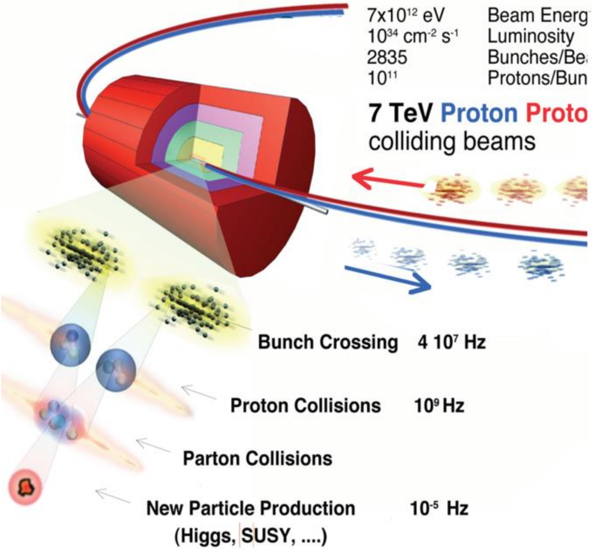
27 km circumference

100 m underground

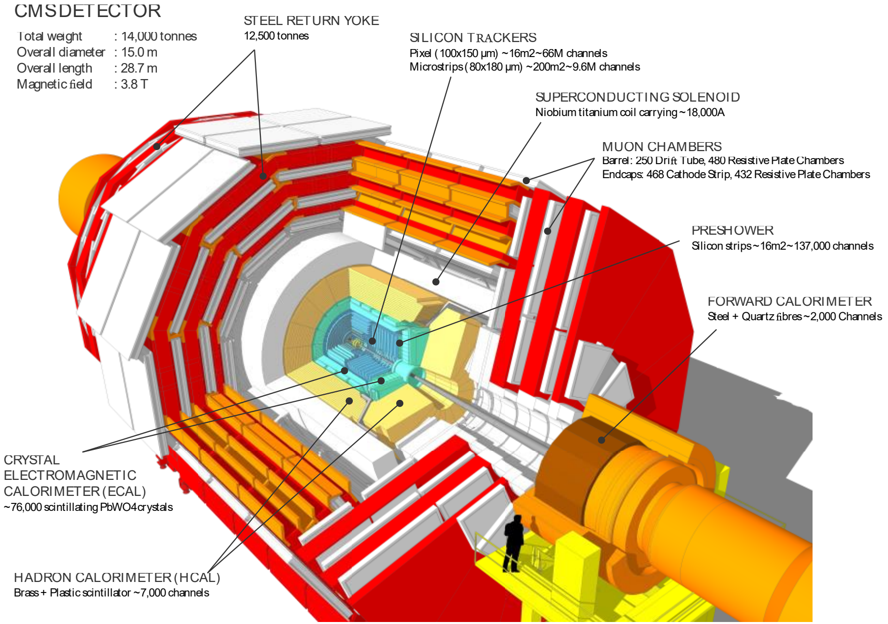
4 caverns for experiments

Proton collisions at LHC



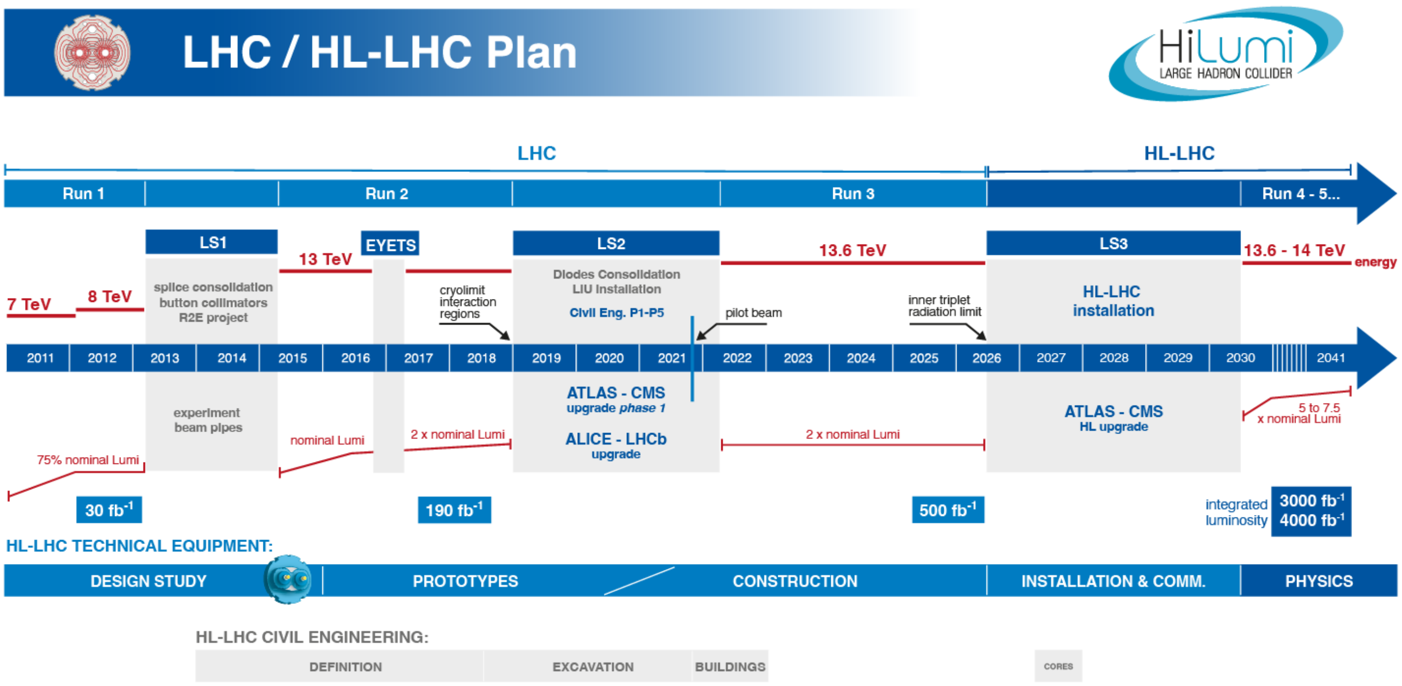


The Experiments

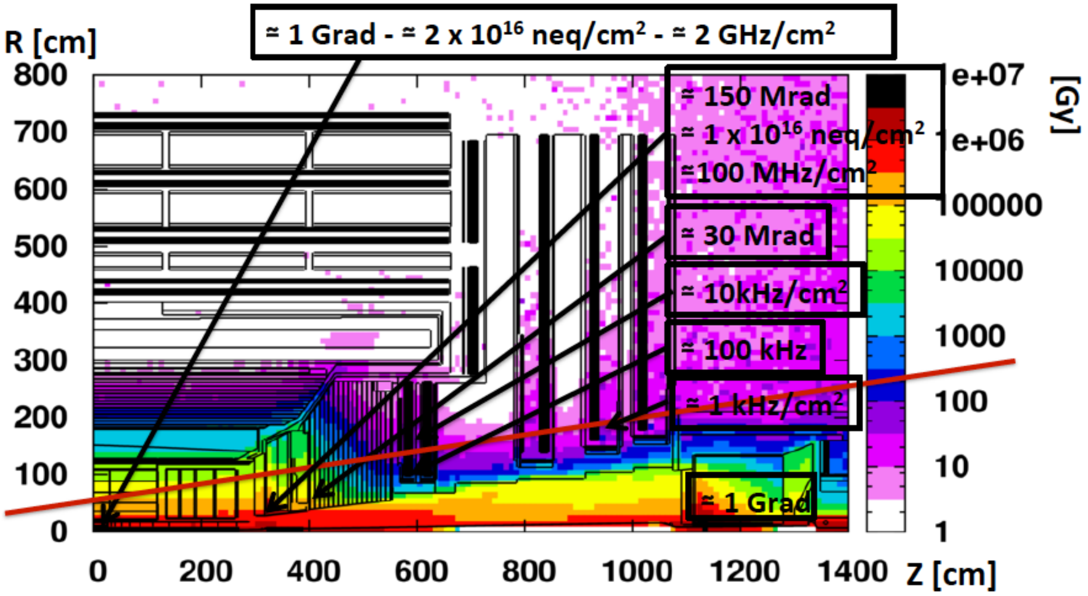


- General purpose detectors (ATLAS & CMS)
  - Large magnetic field (4 T, 4m diam)
  - Central tracker (charged particles)
  - Calorimeters (electrons, photons, hadrons)
  - Muon detectors
- Up to 100 millions electronics channels
  - On-detector electronics tolerant to radiation

The LHC timeline



Radiation challenge at HL-LHC



CMS radiation dose map, neutron equivalent fluence and particle rates for luminosities of 3000 fb^{-1} (integrated) and 5 x 10^{34} Hz/cm^2 (instantaneous)

Big challenge for the new front-end electronics systems.

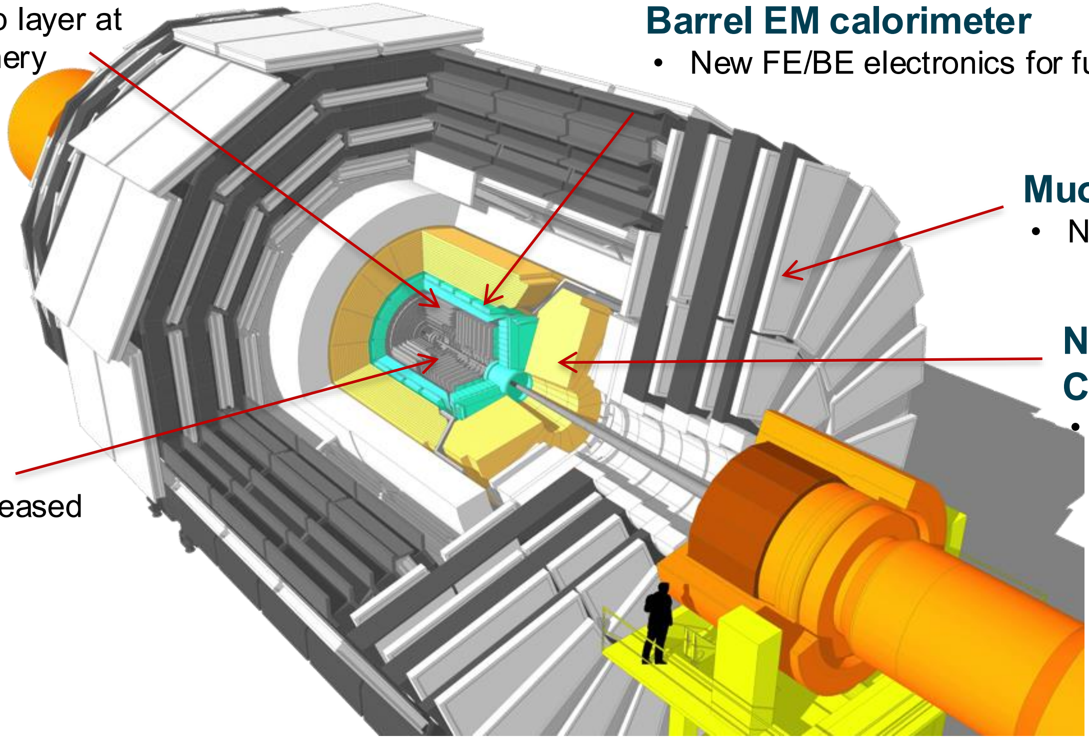
Activation of materials becomes an issue for detector maintenance

Higher bandwidth & full granularity readout

HL-LHC: CMS upgrades

New Timing Detector
- Barrel and Endcap layer at the Tracker periphery

Barrel EM calorimeter
- New FE/BE electronics for full granularity readout

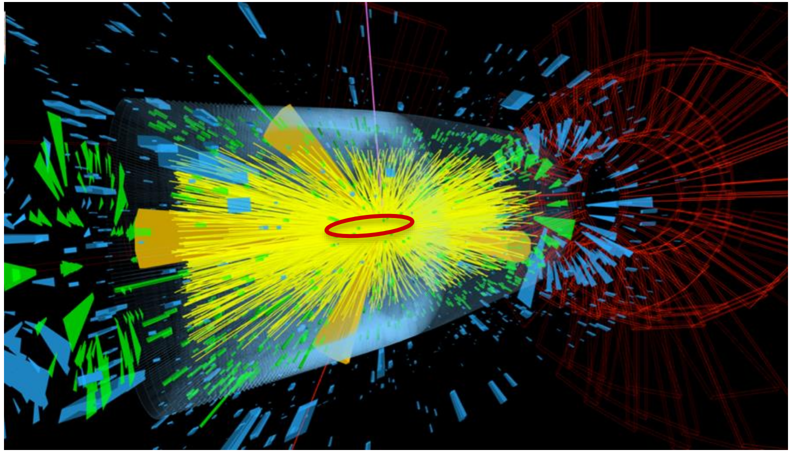


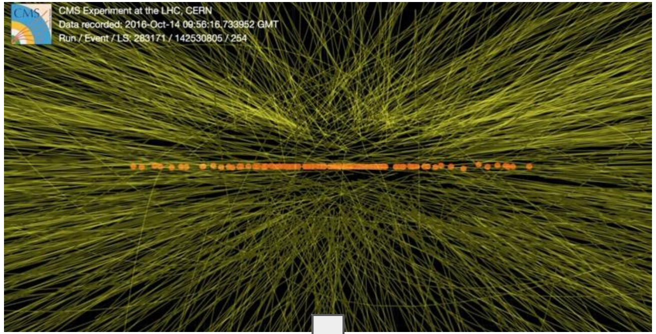
Muon systems
- New electronics

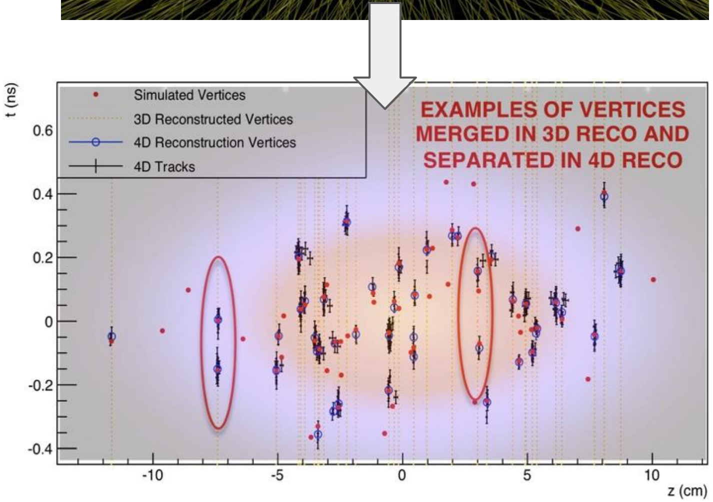
New Endcap Calorimeters
- Rad. tolerant - increased segmentation

New Tracker
- Rad. tolerant - increased granularity

New paradigm: Timing







- At HL-LHC up to **140-200** nearly-simultaneous collisions (**pileup**)
- **Precision Timing Detectors with tens-of-ps resolution** allows recovering current LHC level of vertex merge rate & track purity

Timing jitter

$$\sigma^{BTL}_t = \boxed{\sigma^{clk}_t} \oplus \boxed{\sigma^{disc}_t \oplus \sigma^{elec}_t} \oplus \boxed{\sigma^{photo}_t \oplus \sigma^{DCR}_t}$$

Digital TOFHiR Crystal & SiPM

- Purpose – detect and time-tag valid MIP events with a time resolution <50ps average throughout the detector lifetime

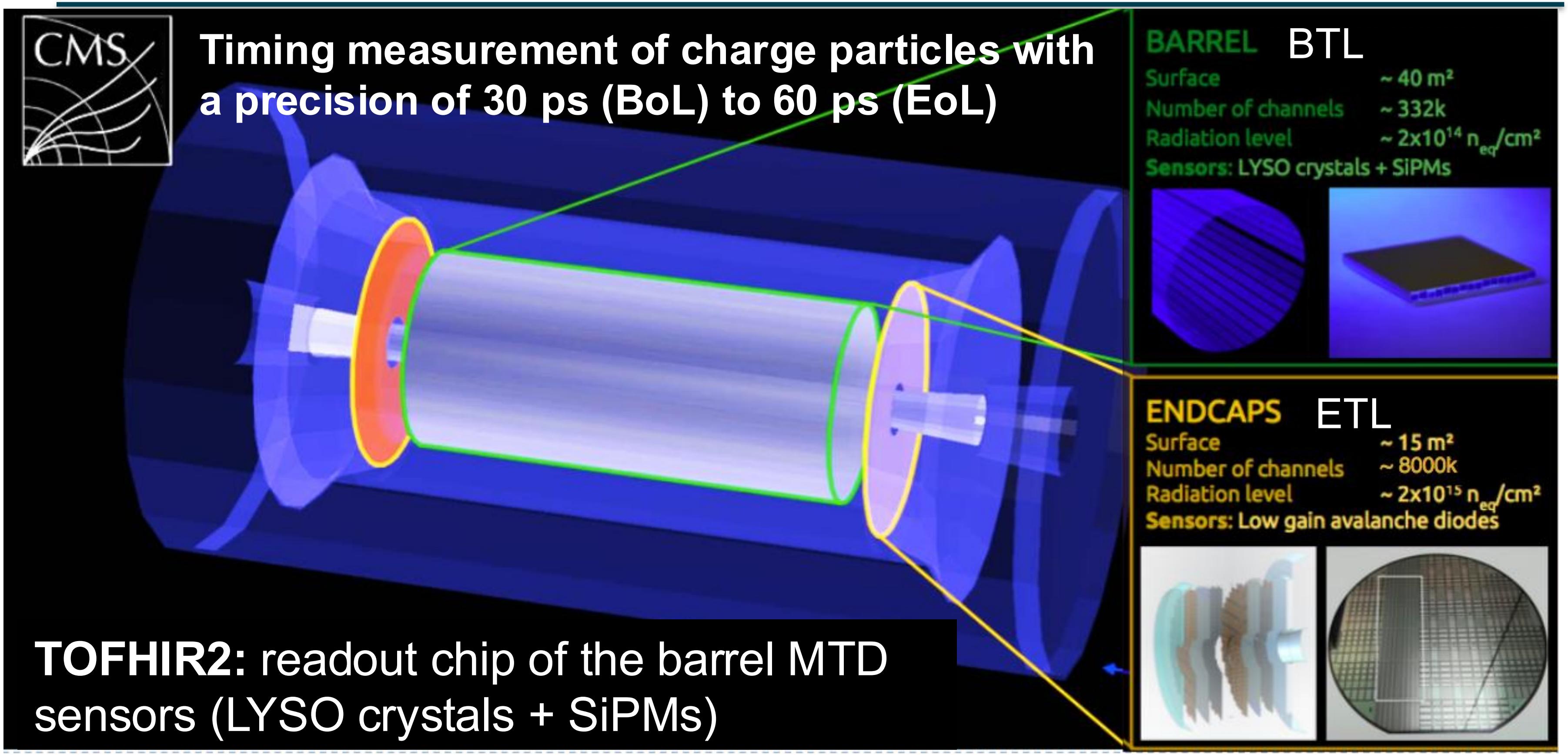
- There are three main contributors to time resolution
  - Digital clock jitter
  - TOFHiR - Time discritizations in the TDC & electronics noise
  - Crystal photo-statistics & dark counts

- Note (dark counts)
  - Long time exposure to high radiation levels damages SiPM
  - Thermally generated small current pulses at high rates (up to 20GHz)
  - Mitigated, to an extent, by lowering operating temperature (-45ºC)
  - Indistinguishable from true photoelectrons generated by MIP events

Electronics systems of the CMS Timing Detector

CMS MIP Timing Detector

Timing measurement of charge particles with a precision of 30 ps (BoL) to 60 ps (EoL)



TOFHIR2: readout chip of the barrel MTD sensors (LYSO crystals + SiPMs)

BTL barrel timing layer

- Cylindrical detector with an active area of ~38 m^2, utilizes LYSO:Ce scintillating crystals coupled with silicon photomultipliers (SiPMs).
- The SiPM signals are processed by the TOFHIR2 ASIC
- The full BTL detector comprises 331,776 electronic channels.
- During HL-LHC operation, the detector will be exposed to high radiation levels, reaching 2×10^{14} n_{eq}/cm^2, leading to SiPM degradation and an increase in Dark Count Rate (DCR) from 0.5 MHz to 10-20 GHz.
- To mitigate dark noise, SiPMs will be cooled to -45°C and periodically annealed at 60°C, and TOFHIR2 implements DCR suppression circuitry

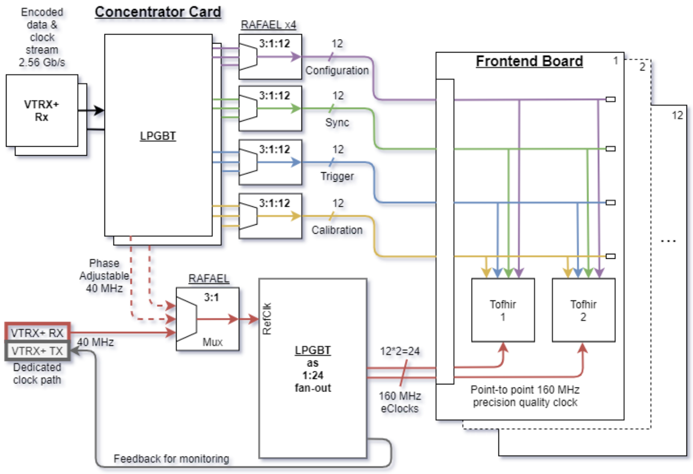
BTL front-end electronics

- BTL front-end electronics is organized in 432 **Readout Units (RU)**
  - 768 channels per RU
- Three types of boards:
  - FE Board (FE)
    - readout chip (**TOFHIR2**); LV and BV regulator (**ALDO2**)
  - Concentrator Card (CC)
    - Giga-Bit transceiver (**lpGBT**) and Versatile Link Plus (**VTRx+**)
    - **RAFAEL** clock fan-out chip
    - **GBT-SCA** for monitoring of low voltage, temperatures, SiPM bias currents
  - Power Converter Card (PCC)
    - DC/DC converter based on the **bPOL12** chip.

Seven radiation tolerant ASICs are required

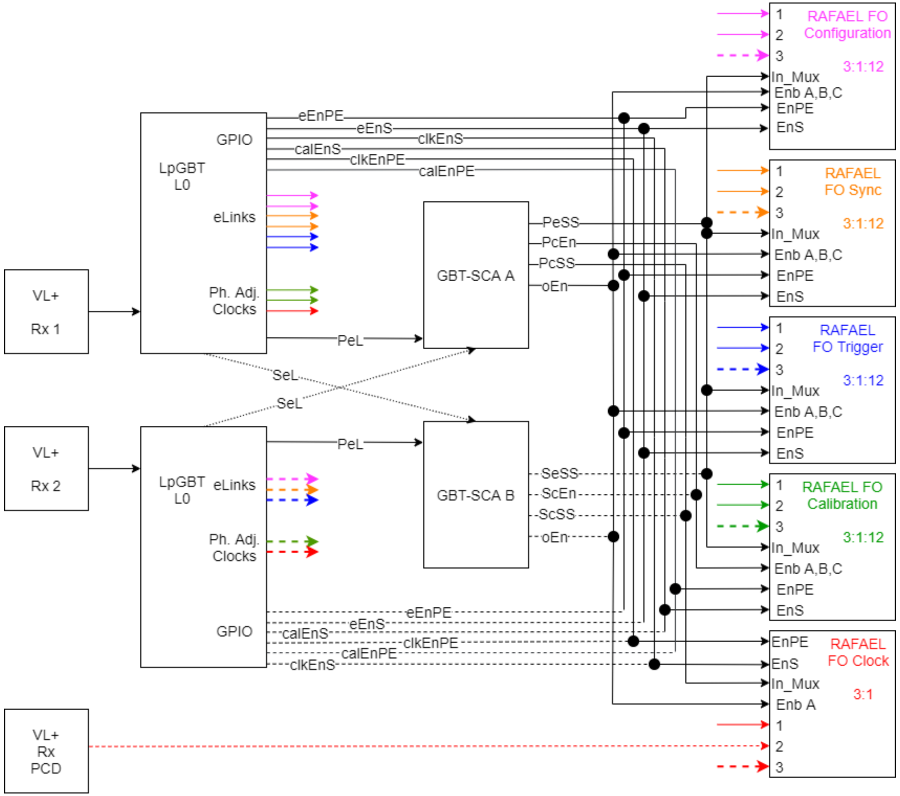
ASICs in BTL electronics

- **TOFHIR readout ASIC** provides the front-end digitization of sensor signals
- **Data and control links implemented with lpGBT and VTRX+ chips**
  - 10 Gbit/s optical data links and 2.6 Gbit/s optical control links
- Two **GBT-SCA** for **slow control and monitoring**
  - ADCs, I/O bits and I2C
- Distribution of clock and control links makes use of the **RAFAEL fan-out ASIC**
- **ALDO2 ASIC** provides low-voltage and SiPM bias-voltage regulation
- **Power distribution** implemented in PCC cards using DC-DC 12V converter **bPOL12 ASIC**



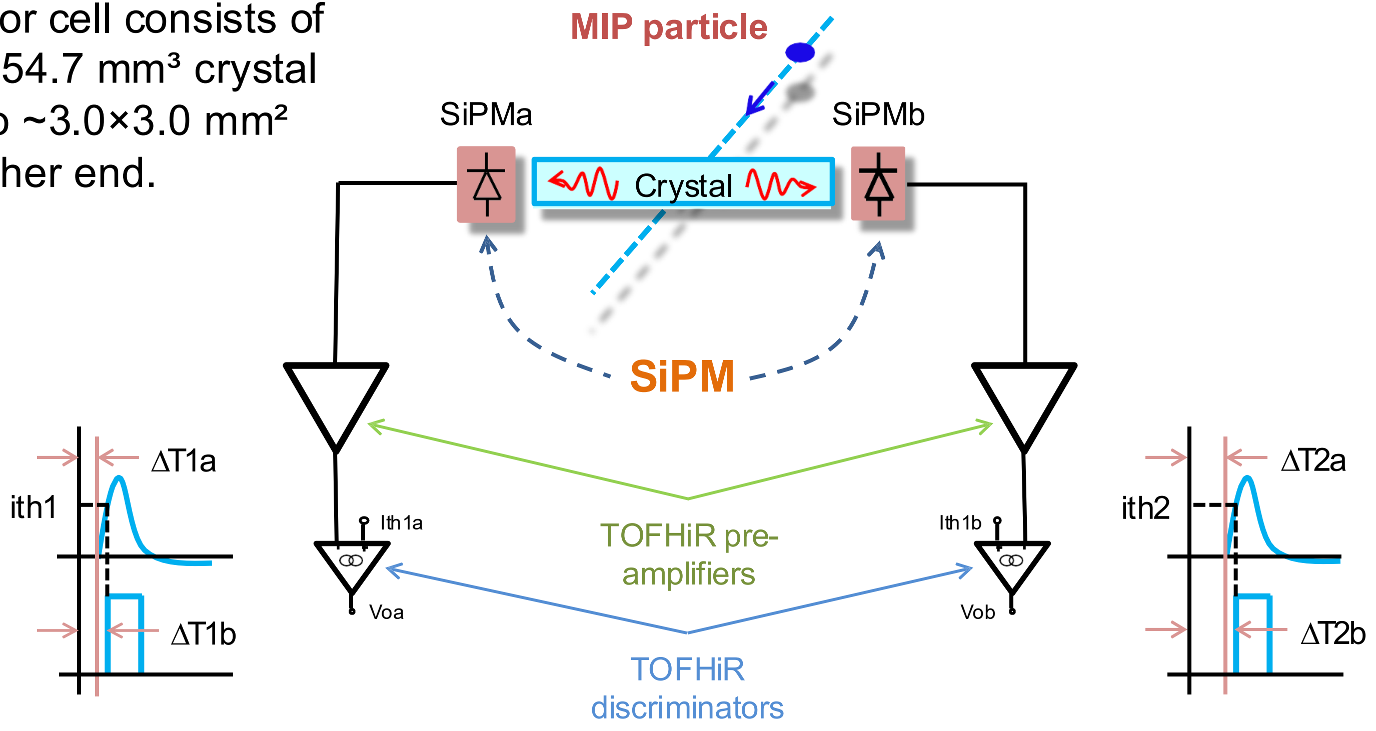
Redundant control and readout

- There is no access to the detector front-end during its lifetime
- Redundancy is required
- Reliability requirements for 10 years lifetime:
  - **99% reliability at 95% CL**
- All electronics boards have been qualified through extensive thermal and power cycles in climatic chambers



BTL sensor and TOFHiR front-end

Each detector cell consists of a 3.0×3.75×54.7 mm³ crystal bar, with two ~3.0×3.0 mm² SiPMs at either end.



Front-end requirements

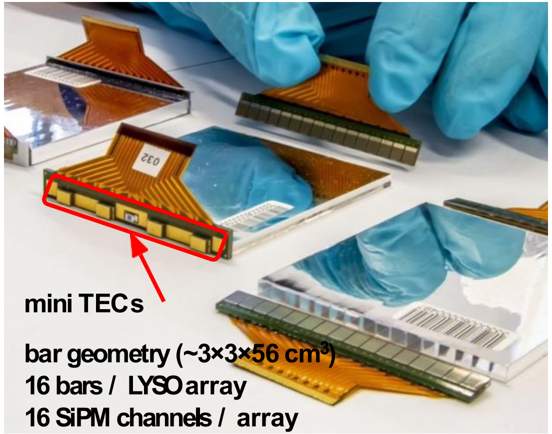
- Particle rate
  - Minimum Ionizing Particles (MIP) rate: 2.5 MHz/channel
  - Low energy hit rate: 5 MHz/channel
- Timing measurement
  - Two timing measurements per event
- Amplitude measurement
  - Charge integration and Time Over Threshold
- Dark counts and out-of-time pileup
  - Mitigate degradation of time resolution due to large SiPM dark count rate (DCR)
  - Cancel long LYSO signal tails to minimize pulse pile-up
  - Stabilize baseline to allow good timing with leading edge discrimination

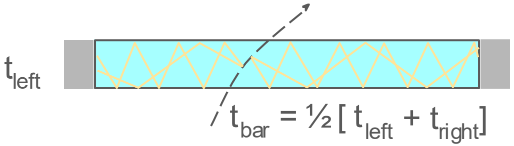
Requirements implemented in the TOFHIR ASIC

BTL sensor technology: LYSO + SiPM

- **LYSO:Ce scintillating crystal bars**
  - fast scintillation rise time (< 100 ps)
  - short decay time (~40 ns)
  - high light yield (~40000 ph./MeV)
  - **tolerant to radiation**

- **Dual SiPM readout for each crystal bar**
  - 25 µm cell size, **mini Thermo Electric Coolers (TECs)**
  - neutron **fluence of 2×10^{14} $n_{eq}cm^{-2}$** expected by the end of HL-LHC (3000 fb^{-1}) → high level of **radiation-induced dark noise**





BTL Detector Module

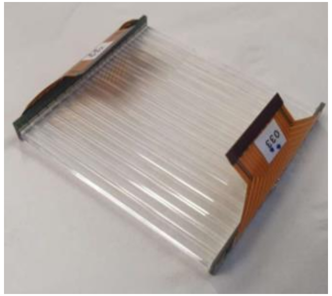
- **BTL sensor module: 16 crystal bars + SiPMs**

- LYSO Crystal Arrays:
  - Scintillating light 30k photons/MeV

- Silicon Photomultipliers:
  - Large dark current noise due to radiation damage (up to 10-20 GHz)
  - SiPMs operated at -45^{o}C (using TECs)

- **Readout ASIC: TOFHIR2**
  - Each Front-End board has 2 TOFHIRs
  - Each TOFHIR has 32 independent channels
  - Low-voltage and SiPM bias provide by ALDO ASIC
  - ~20k chips in BTL detector

BTL sensor module



Front-End board

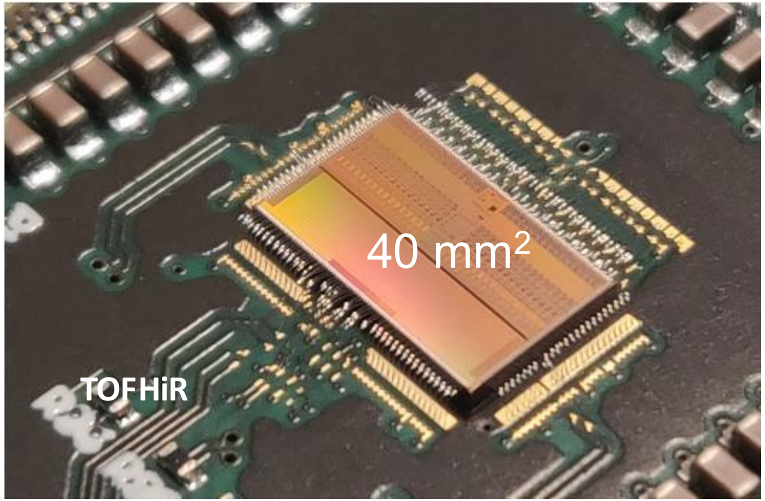
TOFHiR: Key specifications

- Target technology CMOS 130nm (radiation characterized)

- Radiation tolerance
  - Total Ionization Dose (TID) of up to 3 Mrad
  - Particle fluence of up to 2e14 neq/cm^2

- **Time resolution of 50ps average throughout the 10 years detector lifetime**
  - Beginning-of-life (BoL) time resolution 30ps
  - End-of-life (EoL) time resolution 60ps

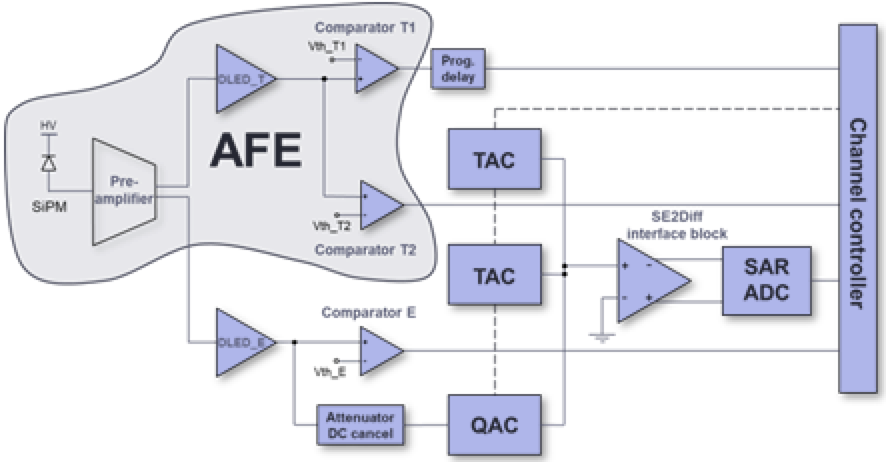
- SiPM dark noise suppression
- Static power dissipation of less than 15 mW per channel
- 32 channels



TOFHIR2 channel

Features:

- Branches: T, E and Q
- Three leading edge discriminators
- Full current mode implementation
- Two TACs and one QAC sharing 40 MHz SAR ADC



TOFHIR2 characteristics	
Number of channels	32
Technology	CMOS 130nm
Voltage supply	1.2 V
Reference voltage	Internal
Radiation tolerance	Yes
DCR noise filter	Yes
Number of analog buffers	8
TDC bin (ps)	10
10-bit SAR ADC (MHz)	40
I/O links	CLPS
L1, L0 Trigger	Yes, Yes
Maximum MIP rate/ch (MHz)	2.5
Max low E rate/ch (MHz)	5
Clock frequency (MHz)	160

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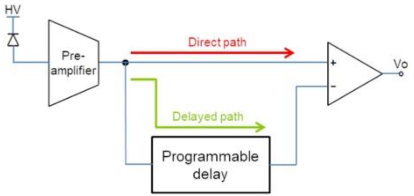
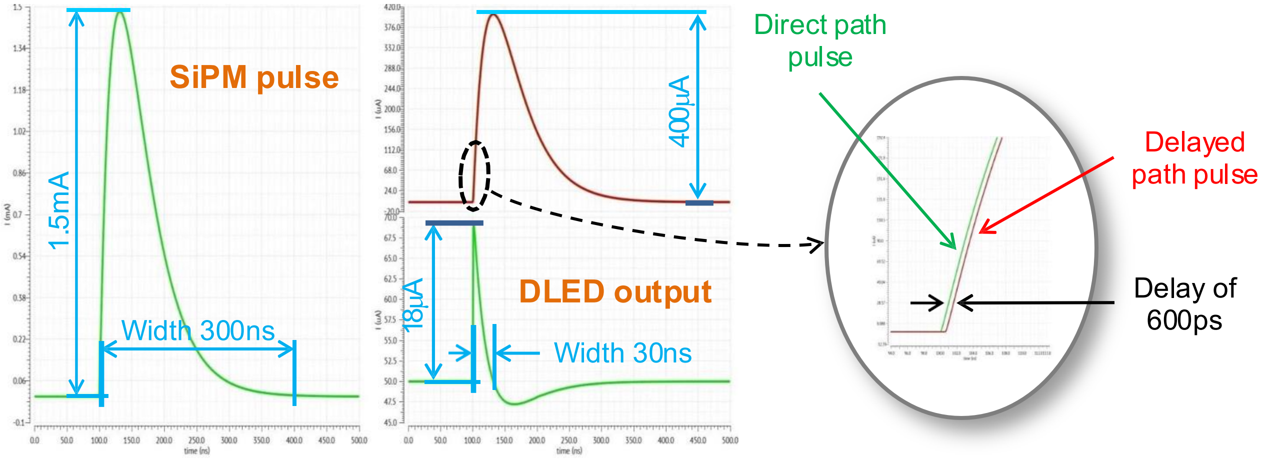
Dark noise suppression with DLED

A delayed current pulse is subtracted from the original pulse (**DLED**) → mitigate noise / baseline fluctuations





- Preserves pulse rising edge
- Narrower pulse width - lower pulse pile-up
- Converts the unipolar SiPM pulse into a bipolar pulse
- Reduced dark noise impact on time resolution

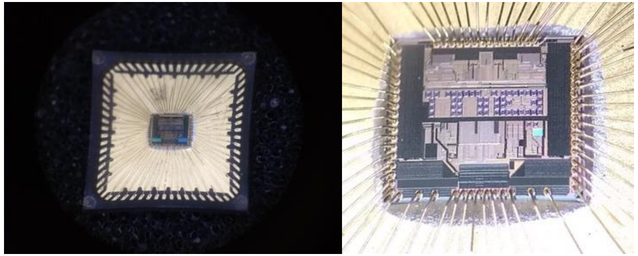
	SiPM ouput current	DLED output current
Slew rate (μA/ns)	135.9	9.93
Noise r.m.s (μA)	24.5	0.51
σ_{noise}/ SR (ps)	180	52

Time resolution is improved by a factor 3.5

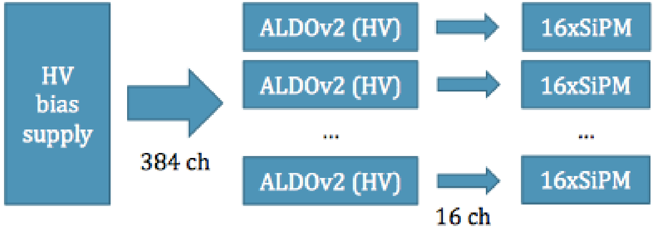
ALDO2 ASIC

Main objectives of the chip:

- SiPM bias voltage regulation
  - Finer segmentation and adjustable regulation
    - 16 channels for each independent bias line
  - Dark current measurement
- TOFHiR low voltage regulation
  - Filter noise on power supply
  - Improve thermal and load stability



SiPM bias voltage regulation (HV)



TOFHiR power supply regulation (LV)

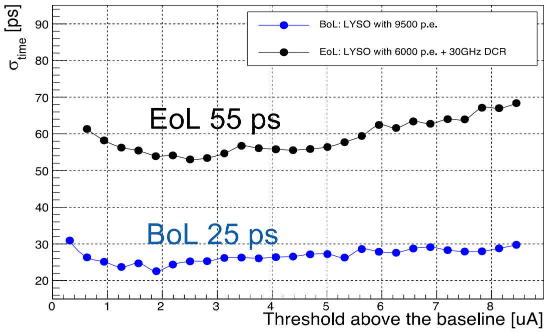
Performance measurements

Time resolution

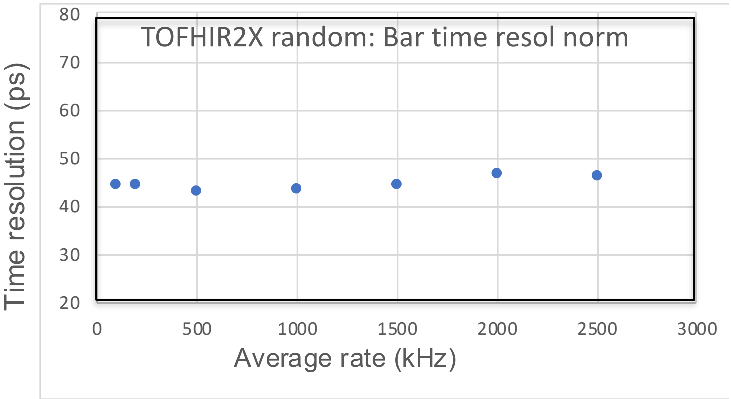
Lab measurements with UV laser

Proton Test Beam

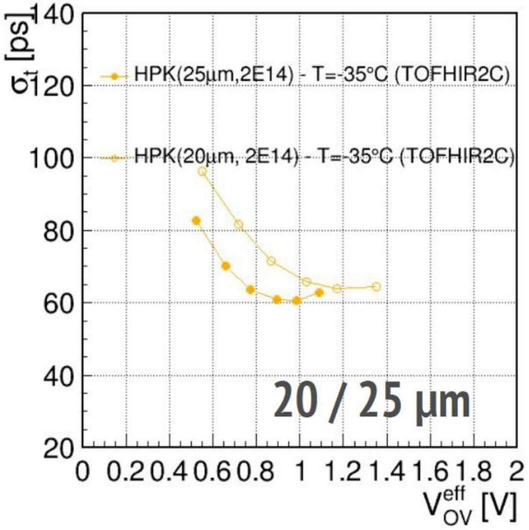
Time resolution at BoL and EoL
Time resolution as a function of threshold in BoL and EoL



Time resolution as a function of rate
Detector module with TOFHIR2 excited with UV laser (pseudo-random test pulses)



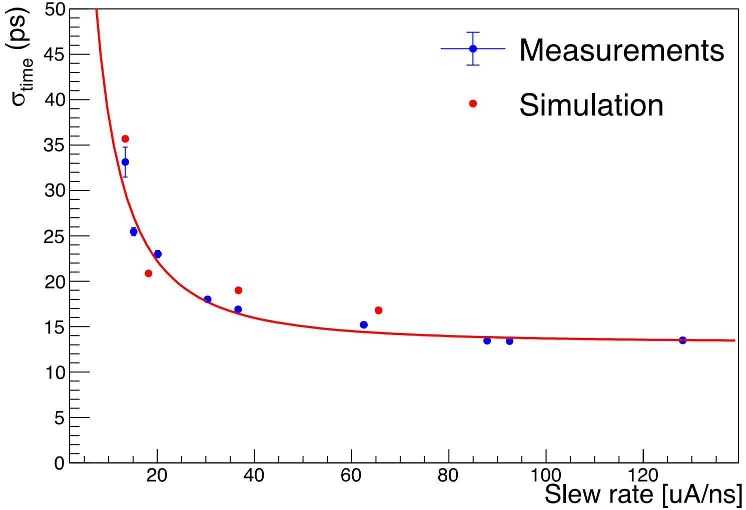
Results with **TOFHIR2 on modules irradiated to 2E14** with 20 and 25 μm SiPMs at T=-35°C



Solid state noise

- The **contributions of the amplifier and TDC noise to the time resolution** are estimated with laser light shining on two naked SiPMs (using a beam splitter)
- The channel time resolution is derived from the measured CTR
- Fit function: $\sigma_t = \sigma_{noise}/(dI/dt) \oplus \sigma_{TDC}$
- Fit result: σ_{noise}= 0.360 µA and σ_{TDC}= 12 ps.
- Electronics noise contribution to time resolution:

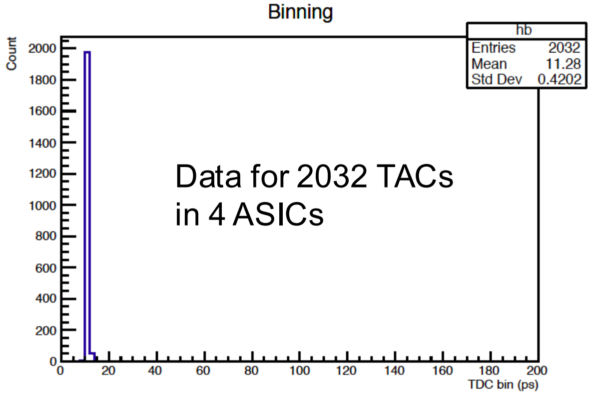
$$\sigma_t^{elect} = \frac{\sigma_{noise} = 0.36\ \mu A}{SR = 28.6\ \mu A/ns} = 13\ ps$$



TDC performance

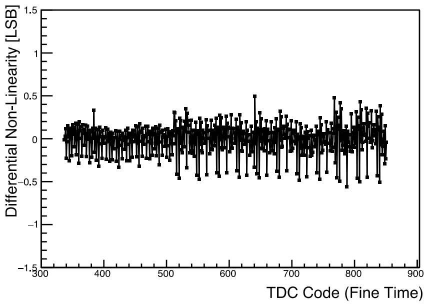
TDC binning:

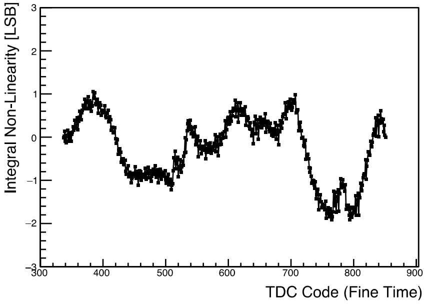
- **Typical binning is 11 ps**
  - 10 ps expected
- Low dispersion of binning
  - sigma=0.4 ps



TDC linearity:

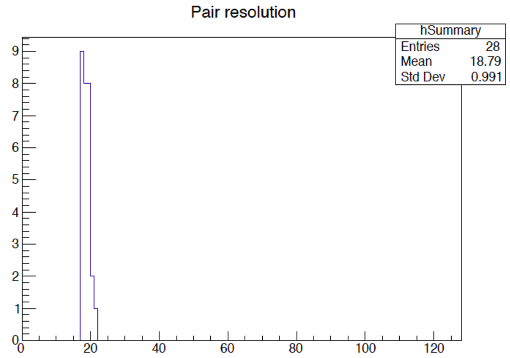
- DNL < ± 0.5 LSB
- INL < ± 2 LSB





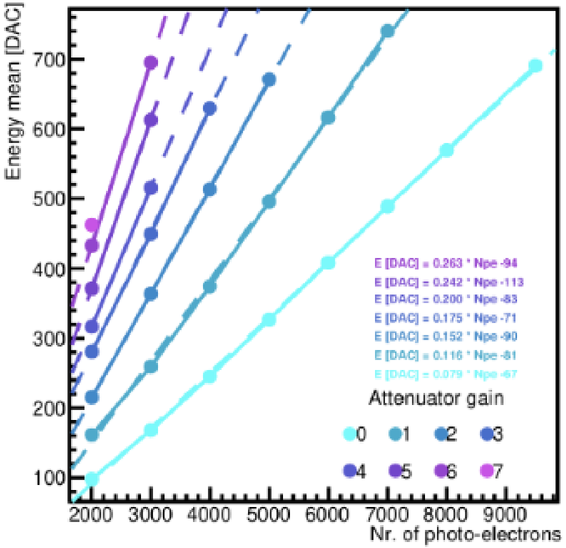
TDC resolution:

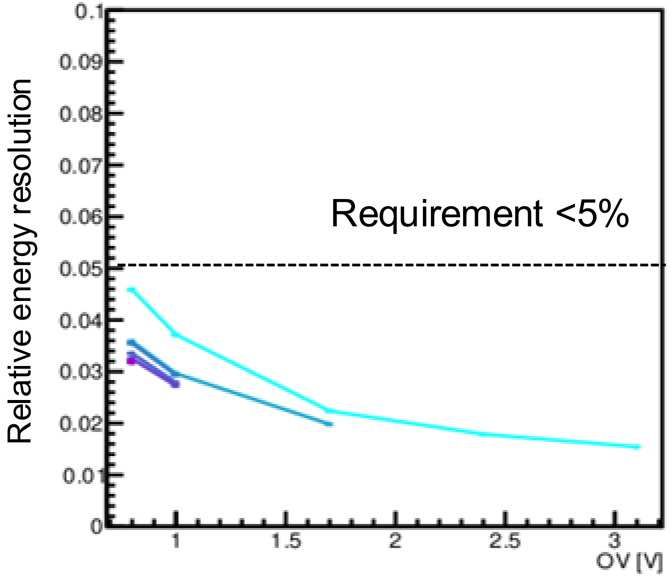
- Coincidences between TDC pairs used to cancel common jitter (e.g. clock jitter)
- **TDC resolution is 13 ps**
  - 5% dispersion



TOFHIR: Energy measurements

- Charge integration block has been validated
  - Good linearity in energy dependence on number of photoelectrons
  - Energy resolution ~2% in the range of pulse amplitude of interest





Radiation tolerance

X-Ray Irradiation Facility at CERN

TID tests done at the x-ray irradiation facility at CERN

– TOFHIR ASICs were irradiated up to 7 Mrad

– Max expected dose in BTL is 2.9 Mrad

Observables:

– Total current consumption

– Bandgap voltage

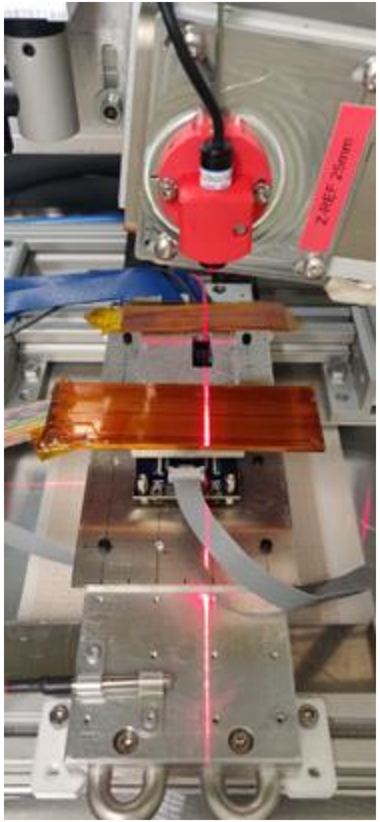
– DAC scan of DC voltages

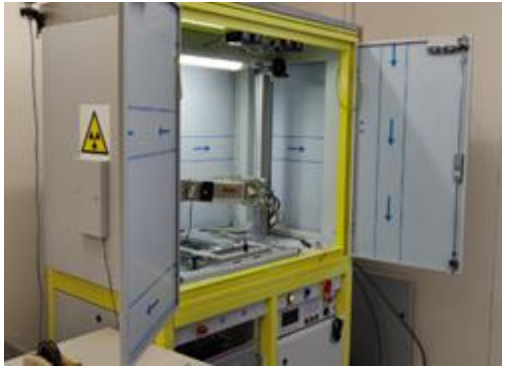
– Front-end noise from threshold scan

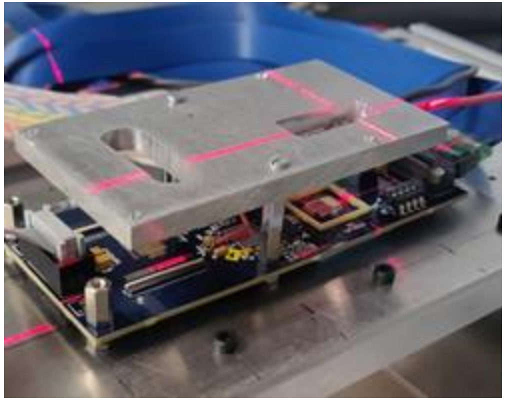
– Shape of analog test pulse from disc. threshold scan

– TDC calibration in all TACs

– QDC calibration in all QACs







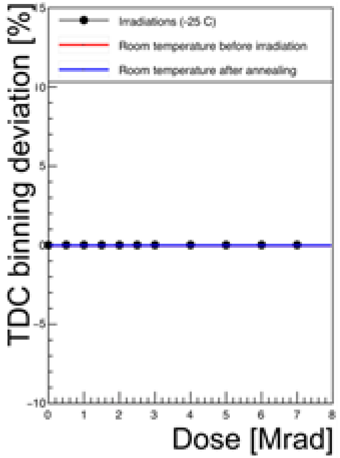
TID Radiation Test of TOFHIR2

– Negligible effects up to 7 Mrad in the frontend amplifiers, TDC and QDC.

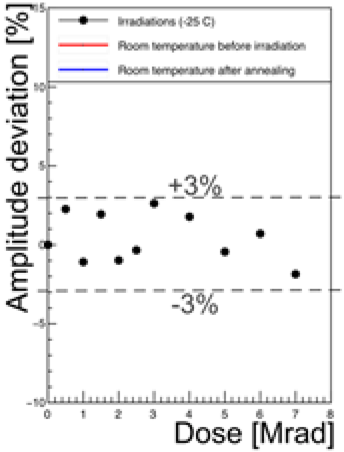
– Emulating radiation and annealing cycles in one year operation

→ Effects up to 6% before annealing
→ No effects larger than 1% after annealing

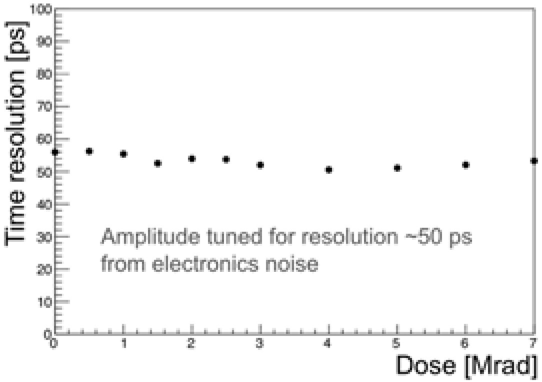
TDC binning



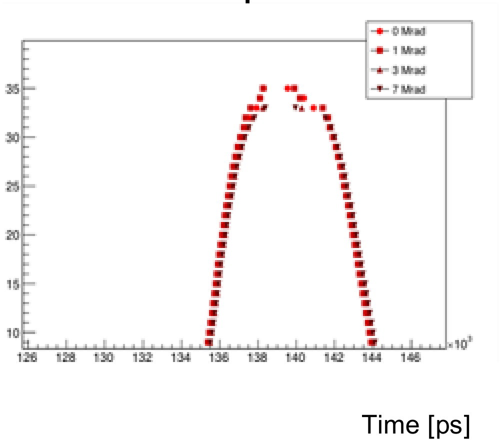
QDC amplitude



Time resolution



Pulse shape



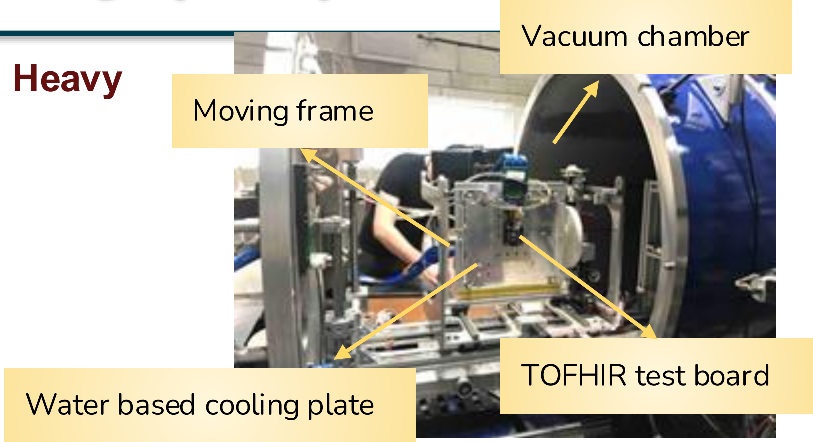
Heavy Ion Facility (HIF)

Tests of Single Event Effects (SEE) were performed at Heavy Ion Facility (HIF) Louvain-la-Neuve

– Different ions covering a wide range of LET and ranges

– Different incident angle for intermediate LET

– Max beam flux is 1.4×10^4 ions/s.cm^2



Observables:

– Cumulative SEU counter (SEU events)

– Synchronization counter (SET)

– Number of configuration bits flipped (non-corrected errors)

M/Q	Ion	DUT energy [MeV]	Range [µm Si]	LET [MeV/(mg/cm²)]
3.25	$^{13}C^{4+}$	131	269.3	1.3
3.14	$^{22}Ne^{7+}$	238	202.0	3.3
3.37	$^{27}Al^{8+}$	250	131.2	5.7
3.27	$^{36}Ar^{11+}$	353	114.0	9.9
3.31	$^{53}Cr^{16+}$	505	105.5	16.1
3.22	$^{58}Ni^{18+}$	582	100.5	20.4
3.35	$^{84}Kr^{25+}$	769	94.2	32.4
3.32	$^{103}Rh^{31+}$	957	87.3	46.1
3.54	$^{124}Xe^{35+}$	995	73.1	62.5

SEE radiation test

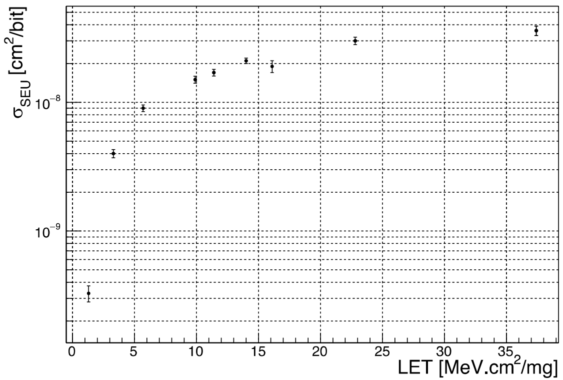
- **SEE protection in TOFHIR2:**
  - TMR on configuration bits (15'558 flip-flops), readout logic and clock/resync trees
  - automatic correction of SEUs

- Measurements of Single Event Effects (SEE) were performed at Heavy Ion Facility (HIF)

Results extrapolated to HL-LHC:

- Cross-section of SEU errors
  - cross-section of corrected errors at HL-LHC is about ~10^{-10} cm^2/chip
  - ratio of uncorrected/corrected errors is of the order of 1/1000
- Rate of uncorrected SEE errors at HL-LHC:
  - charged particle rate in BTL ~ 10^6 cm^{-2} s^{-1}
  - estimated rate of uncorrected errors or synchronization losses is ~10^{-7} /chip/s.

Cross-section of corrected SEU errors



Conclusions

- Front-end electronics systems for the MTD/BTL detector of CMS have been successfully developed.
- Two dedicated rad tolerant ASICs have been developed specifically for this detector: the signal processing TOFHIR and the voltage regulator ALDO.
- Five other rad tolerant general-purpose ASICs designed at CERN have also been used. These ASIC can sustain radiation up to 150 Mrad (1.5 MGy) and 1.5×10^7 $n_{eq}/cm^2/s$ (1 MeV neutron equivalent fluence).
- Extensive measurement campaigns show that the average time resolution of 50 ps is met throughout the 10 years detector lifetime.
- Radiation tolerance of the BTL ASICs TOFHIR and ALDO have been validated for TID up to 7 Mrad (70 kGy) and fluence of 10^6 $n_{eq}/cm^2/s$.